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Geodesy and Geodynamics xxx (xxxx) xxx

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepage: http://www.keaipublishing.com/geog

The usability of GNSS mass-market receivers for cadastral surveys considering RTK and NRTK techniques

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ARTICLE INFO

Article history:
Received 5 December 2018
Accepted 10 April 2019
Available online xxx

Keywords:
GNSS
Cadastral surveying
RTK
NRTK positioning
Mass-market receivers

ABSTRACT

Nowadays many positioning techniques and methods are applied to the cadastral surveys. Starting from last decade, GPS/GNSS positioning had become one of the most used methodology thanks to the rapid development of satellite-based positioning and to the appearance of GNSS mass-market receivers and antennas. Methods based on these instruments are more affordable than the conventional ones even if their use for precise positioning is not so intuitive. This study is aimed to evaluate the use of single-frequency GPS/GNSS mass-market receivers for cadastral surveys, considering both single-base Real-Time Kinematic (RTK) and Network Real-Time Kinematic (NRTK) methodologies. Furthermore, a particular tool for predicting and estimating the occurrence of false fix of the phase ambiguities has been considered, in order to improve the accuracy and precision of the solutions. Considering the single-base positioning, the research results showed the difference of a few centimetres between the reference coordinates and the estimated ones if the distance between master and rover is less than 3 km, while considering the network positioning and the Virtual Reference Station correction, the difference are about a couple of centimetres for East and North component, and about 5 cm for the Up.

1. Introduction

Surveying can be defined as the technique useful to determine the absolute or relative three-dimensional position of points on the Earth' surface or above it [1,2]. Surveying techniques have rapidly improved with the development of technology. Considering land surveying, it has gone from ancient techniques, such as tachymeter, geodimeter, to electro-magnetic distance meter, total stations, up to laser scanners and GPS/GNSS receivers [3–5].

An improvement in terms of accuracy and time of surveying has been obtained since the appearance of satellite-based global positioning system, as described in literature [6–14]. In early 1990s, it was necessary to collect a few hours of GPS measurements in static mode in order to estimate the phase ambiguities as integer value, for achieving accuracies of few centimetres. With the advent of multi-constellations (GLONASS, Galileo and Beidou satellites, in addition to the GPS constellation) and thanks also to the developments in the satellite and receiver systems over the next twenty years, new techniques based on high-precision real-time kinematic (RTK) surveying have been developed, using one or more fixed base stations with known coordinates (called master) and one receiver which position is unknown, defined as rover [1,15–17]. This has allowed the increasing of the distance between the master and the rover stations and the decreasing of the time of surveying [18]. These two parameters are linked to each other: the development of network of permanent stations has allowed the better estimation of the atmospheric biases and phase ambiguity values, decreasing the time interval for obtained a “fixed” solution (where fixed means that phase ambiguities are estimated and defined as integer values). Since last decade, the GNSS mass-market receivers have been employed for precise positioning, considering some shrewdness in terms of positioning techniques, in order to reduce the noise of measurements and to improve the accuracy and precision [19].

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2019.04.006

These instruments are more portable than the geodetic ones and they can be used also for a particular type of surveying known as cadastral surveys, where the borders of property, designing, planning and regulations must be defined [20]. This kind of survey was previously based on the control of horizontal and vertical positions of points with high precision: the classical approach is based on measuring angles and distances to determine height differences, areas and volumes using total stations and reflectors. Starting from early 2000s, also GPS/GNSS instruments have been introduced for these kinds of applications [20–23]. In other words, cadastral surveys are made to determine the current real property boundaries. For this purpose, spatial measurement techniques and legal regulations must be used by a land surveyor to determine the position of parcel corners and property boundaries.

In this study, it is aimed to investigate the positioning results performed by different GNSS techniques for cadastral surveying if GNSS mass-market receivers are employed. The attention has been focused to evaluate and compare the accuracy, precision and practical usability of different low-cost single frequency GNSS receivers for cadastral surveying in real-time. These instruments are really interesting because they are cheaper and portable if compared to the geodetic ones and they can provide interesting results at the same time, if used properly. Finally, a robust statistics tool [24] for real-time False Fix prediction is evaluated as the scientific contribution for the quality criteria. Hence, the efficiency and accuracy of the obtained results can be assessed. The rest of the paper is organized as follows. Section 2 discusses the GNSS RTK positioning methodologies if mass-market receivers are considered. Section 3 presents the case study and the surveying results with a discussion, while Section 4 concludes the paper.

2. RTK positioning with mass-market receivers

The use of GNSS mass-market receivers for real-time applications is widespread for many reasons, especially for their low cost and portable dimensions. Very often these receivers are assembled in ‘evaluation kits’ (composed of a receiver and a patch antenna) with a cost less than 80$ and are able to track not only the GPS satellites, but also the GLONASS [24], Beidou and Galileo constellations. Some of them are also able to perform a Network Real-Time Kinematic (NRTK) positioning [26,27] and, in some cases, to store raw data (pseudorange, carrier-phase, and Doppler measurements) in their internal memory. In the following paragraphs, a brief overview about how it is possible to use this kind of devices for RTK positioning will be provided, focussing the attention on the single-base and NRTK positioning techniques.

2.1. Classical single base RTK-GNSS surveying

The classical approach for real-time kinematic (RTK) positioning is the single-base method. It consists of one master station, settled in a point with well-known coordinates, and one rover device used for measuring the unknown coordinates of the points in real time. First, to understand the RTK positioning concept, it is necessary to recall some concepts about differential positioning. So, eq. (1) represents the pseudorange (up) and carrier-phase (down) relation in units of length [27]:

$$\begin{aligned} R^p_{k|i}(t) &= \rho^p_k(t) - cdT_k(t) + cdt^p(t) + \alpha_i I^p_k(t) + T^p_k(t) + M^p_{k|i}(t) \\ &\quad + E^p_k(t) + \varepsilon^p_k(t) \\ \phi^p_{k|i}(t) &= \rho^p_k(t) - cdT_k(t) + cdt^p(t) - \alpha_i I^p_k(t) + T^p_k(t) + M^p_{k|i}(t) \\ &\quad + E^p_k(t) + \lambda_i N^p_{k|i} + \varepsilon^p_k(t) \end{aligned} \tag{1}$$

In these equations, $R^p_{k|i}(t)$ and $\phi^p_k(i)$ represent the pseudorange and carrier-phase measurements in units of length respectively between the satellite p and the receiver k on the i-th frequency. On the right-hand side of the equation, in addition to the geometric range ρ^p_k, it is possible to find the biases related to receiver and satellite clocks multiplied by the speed of light (cdT_k and cdt^p), the ionospheric propagation delay $\alpha_i I^p_k$ (with a known coefficient $\alpha_i = f_1^2/f_i^2$ that depends on the i-th frequency), the tropospheric propagation delay T^p_k, the multipath error Mi^p_k, the ephemeris error E^p_k, the carrier-phase ambiguity multiply by the wavelength $\lambda_i Ni^p_k$ and, finally, the random errors ε^p_k. It is important to remind that, in this equation, all elements depend on time except to the carrier-phase ambiguity.

In the traditional single-base RTK positioning, the master station (defined with the letter A) has known coordinates so it can evaluate all GNSS biases, estimating the Pseudo Range Correction (PRC, eq. (2)) and Carrier Phase Correction (CPC, eq. (3)), if pseudorange and carrier-phase measurements are considered, respectively.

$$\begin{aligned} PRC^p(t) &= \rho^p_A(t) - R^p_A(t) - cdt^p(t) - cdT_A(t) = \alpha I^p_A(t) \\ &\quad - T^p_A(t) - E^p_A(t) \end{aligned} \tag{2}$$

$$\begin{aligned} CPC^{(t)} &= \rho^p_A(t) - \phi^p_A(t) - \lambda N^p_A - cdt^p(t) \\ &\quad - cdT_A(t) = -\alpha I^p_A(t) - T^p_A(t) - E^p_A(t) \end{aligned} \tag{3}$$

After this estimation, the master station can broadcast the PRC and CPC values to the rover receiver (defined as B), that it applies these, considering eqs. (4) and (5).

$$\begin{aligned} R^p_B(t)_{\text{correct}} = R^p_B(t) + PRC(t) &= \rho^p_B(t) - cdT_{AB}(t) + \Delta E^p_{AB}(t) \\ &\quad - \Delta I^p_{AB}(t) + \Delta T^p_{AB}(t) \end{aligned} \tag{4}$$

$$\begin{aligned} \varphi^p_B(t)_{\text{correct}} = \rho^p_B(t) + CPC(t) &= \rho^p_B(t) - cdT_{AB}(t) - \lambda N^p_{AB} + \Delta I^p_{AB}(t) \\ &\quad + \Delta T^p_{AB}(t) + \Delta E^p_{AB}(t) \end{aligned} \tag{5}$$

When the distance between the two receivers is lower than 10 km, the atmospheric propagation delays and the ephemeris errors are not irrelevant but can be considered almost the same in both places. Therefore, they are almost eliminated by differencing measurements of the two receivers, allowing centimetric level of accuracy if the phase ambiguity N^p_{AB} is defined (or fixed) as integer number [27]. Over this distance, these errors increase and cannot be neglected. Otherwise, atmospheric errors are spatially correlated and can be spatially modelled (as detailed in [27–29]).

In order to transmit the corrections in real-time, a communication link (by radio waves or GSM links) between both receivers is needed. Moreover, it is also possible to add some constraints (e.g., the length of the baseline) in order to strength the solution, as described in [30]. As shown in eqs. (4) and (5), for GNSS RTK surveys both pseudoranges and carrier phase measurements are considered, whereby users can obtain centimetre level position accuracy in real time [31,32], if the ambiguity resolution is resolved. Many ambiguity resolution methods are available today, but the on-the-fly (OTF) technique a one of the most used in real time [33]. The GNSS biases (mainly ionospheric and tropospheric delays and phase ambiguities for all visible satellites) are estimated at the master station at epoch t_0, while the position at the rover site is performed applying these corrections propagated considering the time interval between the estimation epoch (t_0) and the instant when the corrections are applied [8,33].

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2.2. Network RTK surveying

It is possible to define a network of permanent stations as an infrastructure consisting of three main parts:

- all GNSS permanent stations settled in a certain area (the mean inter-station distance varies from 40 km up to 100 km), with accurately known positions, that transmit their data to a control center in real-time [44];
- a control center, composed by a server, that receives and processes all stations' data in real-time, trying to fix the phase ambiguities for all satellites of each permanent station and to estimate all biases (e.g. ionospheric and tropospheric delays, etc.);
- the network products, which contain the corrections that the rover receiver must apply in order to perform a NRTK survey. These products are provided by the control center and are broadcasted to the user.

It is possible to obtain different levels of accuracy in real-time, in function of the type of receiver (whether it is multi frequency, single frequency or low-cost) and antenna (whether it is patch, mass-market or geodetic) used, as well as also the size of the network dimension [34].

Besides the raw measurements of GNSS permanent stations, it is possible to obtain from the control center the stream data called 'differential corrections', in order to perform real-time positioning. These differential corrections are usually broadcasted according to the Radio Technical Commission for Maritime Services (RTCM) standard (RTCM commission) [35], considering the Networked Transport of RTCM via Internet Protocol (NTRIP) authentication protocol (https://en.wikipedia.org/wiki/Networked_Transport_of_RTCM_via_Internet_Protocol). The biases estimated from the control center are spatially highly correlated and can be interpolated in the position of the various rover receivers in three main ways, as described in [36]:

- Master Auxiliary Concept (MAC): the data from one of the CORSs, called 'master', and the first differences of some other master stations that are close to the rover receiver, called 'auxiliary', are transmitted to the rover. As a dual-frequency instrument is required, this approach cannot be followed by mass-market receivers because they do not have sufficient computing power for using this technique and they do not use more than one GNSS frequency.
- Flächen-Korrektur-Parameter (FKP): the network models all biases inside the network area using very simple linear functions, and transmits the data of a station, usually the closest to the rover, together with the parameters of this model. The rover must interpolate these data in its position and to apply this considering its approximate position.
- Virtual Reference Station (VRS®): the network software models and also interpolates all biases in the rover receiver position, as if they came from an existent real master station. In this case, the rover must transmit to the control center its approximate position (for example through the NMEA, National Marine Electronics Association message) and it can receive the corrections that can be applied in an easy way.

This last method is ideal for single frequency or mass-market receivers, despite it being more complex for the network software. It also allows direct generation from the control center of a 'synthetic' data file that is ideally equivalent to ones that could be generated by a permanent station located near the rover site, particularly useful for post-processing. These files are produced in standard RINEX format and they are also called 'Virtual Rinex'. The two other positioning techniques (MAC and FKP) cannot be exploited because a dual frequency receiver is needed as rover, as described in [36].

Also the Nearest correction (NRT) can be obtained and used in the NRTK approach: in this case, the corrections are obtained directly from the nearest permanent station. Thus, this is not a proper network correction even if the network software computes the network solution with the nearest station and evaluates the correction after this computation. This fact reduces the possibility of a wrong evaluation of biases over that permanent station.

In addition, another possible RTK positioning technique is the PPP-RTK [37,38] that can be applied also to mass-market receivers, as described in [39], but it is not addressed and exploited in this paper.

When the rover receiver uses and applies the differential corrections provided by the network, it can also fix the phase ambiguities and it can reach high positioning accuracy in real-time. In addition to the accuracy and the precision, an interesting parameter that can be analysed is the time-to-first-fix (TTFF) that represents the minimum time that the receiver needs before declaring the phase ambiguities as fixed.

3. Test setup and survey results

In order to investigate the positioning results obtainable by different GNSS techniques for cadastral surveying considering mass-market receivers, a single frequency (L1) and multi-constellation (GPS, GLONASS and Beidou) receiver and a low-cost multi-constellation antenna have been considered. The main characteristics of these instruments are summarized in Table 1.

When using geodetic instruments, the software for obtaining the real-time solution should be provided by the company that sell the device, considering mass-market receivers, this won't happen. So, it is mandatory to consider software which is able to manage GNSS signals and to process them in order to provide a real-time solution. Moreover, geodetic instruments are also equipped by a display that shows results and maps in real-time; again, in the situation of low-cost devices, this won't happen: so, to overcome these problems, it is possible to consider a laptop or a mobile device with a display where GNSS processing software is installed. In this study, a mobile device with a portable version of the RTKLIB (http://www.rtklib.com/) software has been used, considering the RTKNAVI tool for real-time positioning. This software, as already described in bibliography [27,40] is particularly interesting because it allows to manage both raw data (pseudorange and carrier-phase measurements) of many GNSS mass-market receivers (including the u-blox ones) and stream data coming from a network of permanent stations that uses NTRIP authentication. It allows the multi-frequency (L1, L2, L5) and multi-constellation (GPS, GLONASS, Galileo, BeiDou, QZSS) positioning with the possibility to set different kind of parameters, starting from the basic ones (e.g., the cut-off angle) up to more specific ones (e.g., measurement errors on pseudoranges and carrier-phase, process noises, satellite clock stability).

The RTKNAVI tool allows also to fix the phase ambiguities as integer values, using the modified LAMBDA method [41], an interesting technique especially for real-time applications where computational speed is crucial. Indeed, the modified LAMBDA (MLAMBDA) method reduces computational complexity of the "classical" LAMBDA [42]. In this context, it is possible to define the threshold of the ratio test: it means that the software verifies if the ratio between the two best solutions are greater than that threshold value. In case of positive answer, the phase ambiguities are defined as integer values (FIX solution) otherwise are real numbers (FLT solution). Moreover, it is also possible to set the strategy of integer ambiguity resolution. Four different methods can be chosen:

Table 1
Main characteristics of used instruments.

	u-blox M8T	Garmin GA38
Image		
Main Characteristics	GPS: C/A, L1, Doppler, S/N GLONASS: L1 Galileo:E1 Beidou: B1	single frequency (L1) GPS + GLONASS + Beidou

- Continuous: continuously static integer ambiguities are estimated and resolved;
- Instantaneous: integer ambiguity is estimated and resolved by epoch-by-epoch basis
- Fix and Hold: continuously static integer ambiguities are estimated and resolved. If the validation is OK, the ambiguities are tightlyconstrained to the resolved values
- PPP-AR: Ambiguity resolution in PPP

but only the first three methods are useful for NRTK positioning.

Some tests were designed and made in Sassello, a small town of the Liguria Region (Italy), as shown in Fig. 1.

Initially, 16 points have been considered in four different areas (named A, B, C, D), along different boundaries of cadastral parcels, performing a single-base RTK survey. The mass-market master device has been placed on well-known point about 1, 3, 5, 8 and 10 km far from the rover site, even it equipped with the same instruments described in Table 1. Data sets were collected in different times of a day, considering each session length of about 10 min with a sampling rate equal to 1 s and a mean number of GNSS satellites equal to 18 (9 GPS + 5 GLONASS + 4 Beidou); therefore, with various satellite constellations (e.g., satellite visibility, Dilution of Precision (DOP) indexes) ensured the independence of the datasets. In order to compare both precision and accuracy of the estimated RTK solutions, a 3-h static survey of testing a GNSS geodetic instrument is done for each test-site; the results obtained with this high-performances receiver, following a double difference approach considering a permanent station (CAMN) of the Liguria GNSS network (Fig. 2) and the Bernese GNSS software v. 5.2, have been considered as “reference” value for the following analyses.

In Tables 2–4, the main statistical parameters (mean and standard deviation) of estimated RTK solutions with respect to the reference ones for each area are reported. Thus, it is verified that

Fig. 1. The test site in Sassello (NW Italy).

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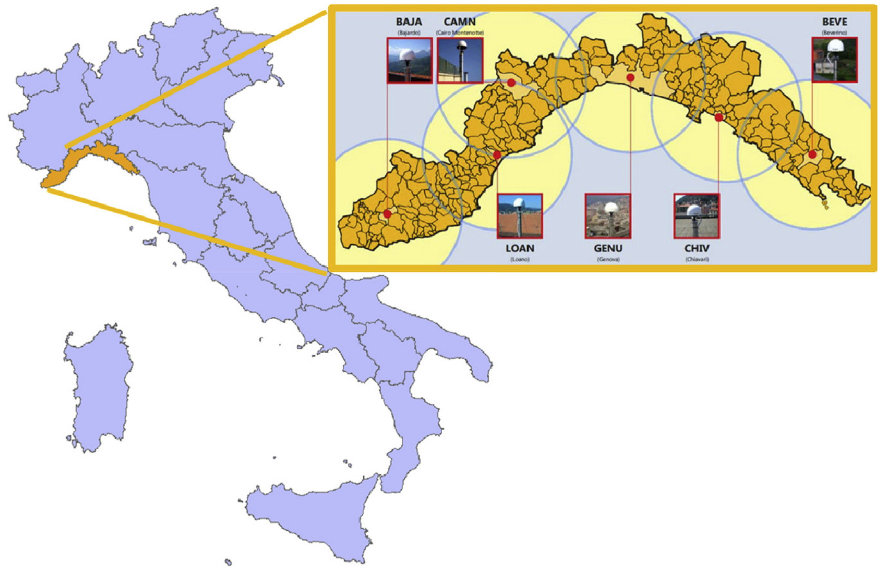

Fig. 2. The NRTK network of the Liguria Region (source: https://geoportal.regione.liguria.it/servizi/rete-gnss-liguria.html).

with this kind of low-cost devices, it is possible to reach a level of accuracy and precision of few cm if a single-base RTK approach is followed, considering the inter-station distance of about 1, 3 and 5 km between master and rover.

If this distance increases to 8 km or 10 km, the performances decrease as shown in Tables 5 and 6, respectively: in these cases, there is no big difference in terms of precision (with a maximum of about 4.5 cm for planimetric components and 8 cm for the Up) while the accuracies get worse, especially for the Up component (up to 28 cm or 34 cm respectively). Thus, in case of distance greater than 5 km between master and rover low-cost receivers, this approach can be considered unfeasible for cadastral applications, because the maximum acceptable error of positioning is about 20 cm for cartographic scale of 1:1000 and about 40 cm for cartographic scale of 1:2000. An alternative interesting solution can be represented by the NRTK positioning: in this context, some tests using the Continuous Operating Reference Stations (CORS) network of the Liguria Region (https://geoportal.regione.liguria.it/servizi/rete-gnss-liguria.html, in Fig. 2) have been done. As previously described, these infrastructures are managed by control centres, which manage and broadcast differential corrections in various ways (VRS®, MAC, FKP) that are well described in literature [36,43]. Unfortunately, these infrastructures are not designed for mass-market receivers; however, the VRS® correction may provide a useful improvement of the positioning accuracies of these receivers, and with some limitations (the low accuracy and the TTFF) the fixing of the phase ambiguities can be achieved.

Considering the same points used for single-base positioning, the NRTK survey has been done using the VRS® correction. In this

Table 2
Differences between reference and estimated coordinates with mass-market receiver using a single-base RTK approach with inter-station distances of about 1 km.

Point name	μE(m)	μN(m)	μh(m)	σE(m)	σN(m)	σh(m)
A	0.004	0.006	0.022	0.008	0.006	0.009
B	0.006	0.011	0.011	0.004	0.010	0.010
C	−0.002	−0.003	0.018	0.006	0.004	0.015
D	−0.004	−0.006	0.009	0.011	0.008	0.012

Table 3
Differences between reference and estimated coordinates with mass-market receiver using a single-base RTK approach with inter-station distances of about 3 km.

Point name	μE (m)	μN(m)	μh(m)	σE(m)	σN (m)	σh(m)
A	−0.008	0.012	0.045	0.010	0.009	0.019
B	0.009	−0.008	0.030	0.003	0.002	0.010
C	0.003	0.004	0.025	0.004	0.005	0.011
D	−0.005	−0.002	0.019	0.008	0.010	0.013

Table 4
Differences between reference and estimated coordinates with mass-market receiver using a single-base RTK approach with inter-station distances of about 5 km.

Point name	μE(m)	μN(m)	μh(m)	σE(m)	σN(m)	σh(m)
A	0.010	−0.011	0.051	0.012	0.007	0.022
B	−0.012	−0.007	0.036	0.018	0.011	0.012
C	−0.008	0.012	0.054	0.014	0.012	0.018
D	0.010	0.011	0.039	0.009	0.006	0.009

Table 5
Differences between reference and estimated coordinates with mass-market receiver using a single-base RTK approach with inter-station distances of about 8 km.

Point name	μE (m)	μN (m)	μh (m)	σE (m)	σN (m)	σh (m)
A	−0.023	0.065	0.232	0.008	0.012	0.013
B	0.048	0.018	0.283	0.012	0.009	0.034
C	−0.035	−0.026	0.162	0.016	0.011	0.031
D	−0.037	0.051	0.129	0.011	0.006	0.026

Table 6
Differences between reference and estimated coordinates with mass-market receiver using a single-base RTK approach with inter-station distances of about 10 km.

Point name	μE(m)	μN(m)	μh(m)	σE(m)	σN(m)	σh(m)
A	0.134	0.046	0.221	0.031	0.034	0.055
B	−0.083	0.038	0.243	0.044	0.038	0.071
C	−0.043	−0.046	0.342	0.028	0.043	0.065
D	0.047	0.061	0.209	0.032	0.046	0.083

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case, as shown in Table 7, there is no substantial difference in terms of precisions and accuracies. Even if the inter-station distance between the closest permanent reference station (CAMN) and the rover receiver is greater than 13 km, the results are better than those obtained with a single-base approach thanks to the generation of a virtual reference station by the software that manage the CORSs network.

In order to generalize the results obtained with the NRTK technique and the devices previously described, other 15 corner points representing cadastral parcels (in Fig. 3) were surveyed using NRTK method: to assess the repeatability of them, four different re-initialization have been done. This means that all points have been acquired four different times, using the same network product, in order to avoid problems due to the ambiguity resolution. In Tables 8 and 9 are summarized the results considering VRS and NRT corrections, respectively. As it is possible to see, using the VRS correction the performances of the rover receiver increase both from the positioning accuracy point of view and from the percentage of epochs where the ambiguities are declared as fixed. This happens because the nearest station (CAMN) is about 13 km far from the rover sites: in these cases, the accuracies are better than those obtainable with a single-base RTK approach because the master station is equipped with multi-frequency and multi-constellation receiver and antenna. So, the biases estimation is more accurate than that in case of using a L1 GNSS receiver.

Sometimes, it happens that the ambiguity resolution method fixes the phase ambiguities in a wrong way: in this case, the

Table 7
Differences between reference and estimated coordinates with mass-market receiver using a NRTK approach with the VRS® correction.

Point name	μE (m)	μN (m)	μh (m)	σE (m)	σN (m)	σh (m)	% of FIX Epochs
A	−0.004	−0.012	0.026	0.018	0.012	0.017	91.3%
B	0.010	0.007	0.019	0.012	0.011	0.013	94.6%
C	0.005	−0.003	0.016	0.014	0.012	0.019	92.4%
D	0.006	−0.004	0.032	0.011	0.010	0.021	92.6%

Fig. 3. The 15 points measured with the NRTK technique considering GNSS mass-market receiver and antenna.

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Table 8
Horizontal and vertical errors obtained considering NRTK surveys with mass-market devices and VRS correction.

Item	Error estimator
East (m)	−0.002
North (m)	0.008
h (m)	0.044
Horizontal residual at 95% (m)	0.009
Vertical residual at 95% (m)	0.063
Percentage of FIX epochs	97.2%
Percentage of FFs	3.6%

Table 9
Horizontal and vertical errors obtained considering NRTK surveys with mass-market devices and NRT correction.

Item	Error estimator
East (m)	0.033
North (m)	0.027
h (m)	0.062
Horizontalresidual at 95% (m)	0.038
Verticalresidual at 95% (m)	0.096
Percentage of FIX epochs	87.2%
Percentage of FFs	4.4%

solution's accuracy is lower than those expected (more than 20 cm against few centimetres) and the positioning results are the worst. This is a typical case called false fix (FF), as deeply described in [44]. In this paper, particular attention has been also paid regarding this aspect: a dedicated tool, already described in [44], has been applied in order to predict and prevent the occurrence of one of these events. Using this shrewdness, it has been possible to exclude all FFs, reducing the percentage from 4% up to 0.6% of epochs. So, it is possible to conclude that these kinds of GNSS receivers coupled with low-cost antennas allow to obtaining a centimetre level of accuracy, useful also for cadastral applications.

4. Conclusions

GPS/GNSS technologies are nowadays used to perform field surveys for different applications, starting from monitoring activities, rapid mapping up to cadastral surveys and pedestrian positioning. GNSS positioning is possible nearly anywhere: the diffusion of GNSS chipset had been possible thanks to their small dimension (few millimetres) that has permitted their integration also in portable devices.

The purpose of this study is to evaluate and compare the accuracy, precision and practical usability of different low-cost single frequency GNSS receivers for cadastral surveying in real-time. Two different techniques have been investigated: the RTK single-base positioning considering both master and rover L1 multi-constellation receivers and the NRTK positioning using the VRS® and NRT corrections.

Specifically, the research intent to evaluate accuracy and precision of these methods and to compare the results obtained by these kinds of instruments with those obtainable with geodetic instruments, and focus the attention on tolerance provided by cadastral applications.

Considering the single-base RTK solutions using L1 GNSS receivers both for master and rover devices, a centimetre level of accuracy can be reached if the baseline length is less than 3 km. If this distance increases to 8 km, the accuracies decrease to 10–20 cm, especially for the up component, so there is no tolerance range of cadastral applications: in fact, if the scale of cadastral map is 1:2000, the graphical error is 40 cm but if the scale is 1:1000, this error boundary is 20 cm, and this methodology does not respect these tolerances. Thus, it is important to switch to NRTK method: considering the VRS® correction, the difference between estimated and reference coordinates are less than 2 cm for planimetric components while are about 5 cm for the Up. Considering the nearest correction, the performances decrease and the residual at 95% are about 4 cm and 10 cm for the 2D and Up components, respectively. Considering the percentage of epochs where the phase ambiguities are declared as fixed, it is possible to conclude that the VRS® correction provides best performances compared to the NRT one: also the percentage of FF is lower than that in the second case. These values decrease if a particular tool is applied which is able to predict and prevent the occurrence of these events: in this case the percentage of FFs decreases from 4% to 0.6% of epochs.

According to the experiences from this study, the use of single frequency GNSS mass-market receivers can be considered useful for cadastral surveys with some adjustments. If the distance between master and rover receivers is less than 5 km, a single-base methodology can be exploited while if the inter-station distance increase it is better to use the NRTK positioning, if a CORS network is available. These results open new perspectives in the GNSS cadastral surveys, allowing to use portable and low-cost devices without loosing accuracy or precision in the estimation of points' coordinates.

Conflicts of interest

The author declares no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geog.2019.04.006.

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Please cite this article as: P. Dabove, The usability of GNSS mass-market receivers for cadastral surveys considering RTK and NRTK techniques, Geodesy and Geodynamics, https://doi.org/10.1016/j.geog.2019.04.006

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Please cite this article as: P. Dabove, The usability of GNSS mass-market receivers for cadastral surveys considering RTK and NRTK techniques, Geodesy and Geodynamics, https://doi.org/10.1016/j.geog.2019.04.006